

# $\gamma$ -rays from molecular clouds illuminated by accumulated diffusive protons from supernova remnant W28

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## ABSTRACT

W28 is one of the archetype supernova remnants (SNRs) interacting with molecular clouds. H.E.S.S. observation found four TeV sources which are coincident with the molecular clouds (MCs) around W28, but *Fermi* LAT detected no prominent GeV counterparts for two of them. An accumulative diffusion model is established in this Letter and the energetic protons colliding the nearby MCs are considered to be an accumulation of the diffusive protons escaping from the shock front throughout the history of the SNR expansion. We have fitted the  $\gamma$ -ray spectra of the four sources and naturally explained the GeV spectral break of the northeastern source (source N) and the nonsignificant GeV emission of the southern sources A and C. The distances of sources A and C from the SNR centre are found to be much larger than those of sources N and B, which may be the basic reason for the faint GeV  $\gamma$ -rays of the two former sources.

**Key words:** radiation mechanisms: non-thermal – gamma rays: theory – ISM: supernova remnants.

## 1 INTRODUCTION

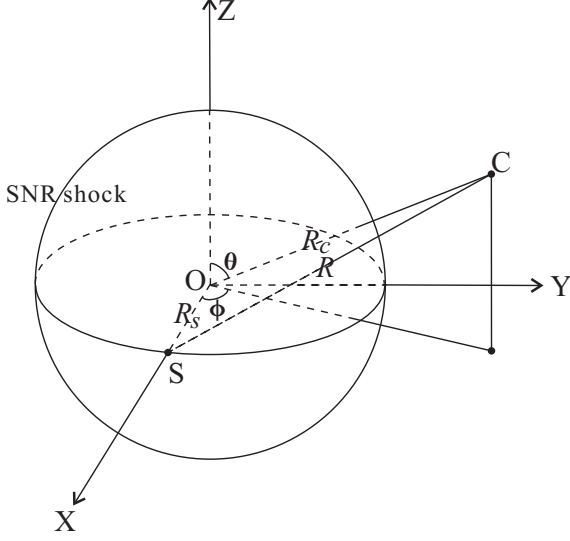
Cosmic rays (CRs) below the “knee” in the Galaxy are commonly believed to be accelerated at the shock of supernova remnants (SNRs). However, whether the  $\gamma$ -rays from SNRs are of hadronic or leptonic origin is still in hot debate. Although evidences for  $\gamma$ -ray emission arising from molecular clouds (MCs) have been found in two SNRs, IC 443 (Acciari et al. 2009) and W28 (Aharonian et al. 2008), it is not easy yet to confirm the emission of the accelerated protons, since the competing lepton processes can also account for the high energy radiation. Fortunately, emission from MCs illuminated by CRs from nearby SNRs (Aharonian & Atoyan 1996; Gabici et al. 2009) can give us opportunities not only to distinguish the contribution of the hadrons from that of leptons but also to investigate the escape process of these energetic protons (Fujita et al. 2009). SNR W28, with recent observation in GeV and TeV  $\gamma$ -rays, is such an excellent case.

W28 (G6.4–0.1) is one of the prototype thermal composite (or mixed-morphology) SNRs, characterized by centre-filled thermal X-ray and shell-like radio emission, with large (about  $50' \times 48'$ ) apparent dimensions (Green 2009). It is considered to be an evolved SNR in the radia-

tive stage, with an age estimate spanning from 35 to 150 kyr (Kaspi et al. 1993). SNR W28 has been confirmed to be interacting with MCs with robust evidences including the 1720 MHz OH masers, morphological agreement with molecular features, molecular line broadening, etc. (see Jiang et al. 2010; and references therein). The observations of molecular lines place it at a distance of  $\sim 2$  kpc (Velázquez et al. 2002).

In  $\gamma$ -rays, H.E.S.S. has revealed four TeV sources in the W28 field positionally coincident with MCs (Aharonian et al. 2008): HESS J1801-233 (denoted as source N in this Letter), located along the northeastern boundary of W28, and HESS J1800-240A, B, and C (denoted as sources A, B, and C, respectively, in below), located  $\sim 30'$  south of W28. Recently, *Fermi* LAT observation (Abdo et al. 2010) found GeV sources 1FGL J1801.3-2322c and 1FGL J1800.5-2359c, which coincide with sources N and B, respectively. More interestingly, it did not detect significant GeV counterparts for sources A and C. The LAT upper limits combined with the H.E.S.S. data imply a spectral break between 10 GeV and 100 GeV. We will show in this Letter that these  $\gamma$ -ray spatial and spectral properties can be accounted for with an accumulative diffusion process of CRs which are accelerated at the dynamically evolving blast shock front.

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**Figure 1.** Sketch for the positional relation between the source point (S) and the field point (C) (see text in §2).

## 2 ACCUMULATIVE DIFFUSION MODEL

CR diffusion models have been developed by Aharonian & Atoyan (1996) and Gabici et al. (2009) to evaluate the CR spectrum in the vicinity of SNRs. In their models, both cases of impulsive and continuous injection are considered on the assumption that the distance between the SNR and the cloud is significantly larger than the size of the SNR, so that the injection region can be approximated as a point-like source. If, however, the cloud is at or close to the SNR blast shock, such as in the case of W28, the diffusion distance for protons injected at various time,  $t_i$ , and various shock radius,  $R_s$ , is not a constant and the assumption of point-like source injection should be modified. Therefore, we here establish an accumulative diffusion model considering that the energetic protons colliding the given MC are a collection of the diffusive protons escaping from different  $R_s$  as the SNR expands. *Small distance between the SNR and MC is allowed.*

The distribution function at an arbitrary field point C (at radius  $R_c$ ) of the energetic protons that escape from unit area at an arbitrary source point S on the spherical shock front surface (see Figure 1) is given by (Aharonian & Atoyan 1996)

$$f(E_p, R(t_i, \theta, \phi), t_{\text{dif}}) \approx \frac{1}{4\pi R_s^2} \frac{dN_0/dt_i}{\pi^{3/2} R_{\text{dif}}^3} \exp\left(-\frac{R^2(t_i, \theta, \phi)}{R_{\text{dif}}^2}\right) \quad (1)$$

where  $R(t_i, \theta, \phi) = \sqrt{R_s^2(t_i) + R_c^2 - 2R_s R_c \sin \theta \cos \phi}$  is the distance between points S and C (Figure 1),  $t_{\text{dif}} = t_{\text{age}} - t_i$  is the diffusion time after the escape,  $R_{\text{dif}} \equiv R_{\text{dif}}(E_p, t_{\text{dif}}) = 2\sqrt{D(E_p)t_{\text{dif}}}$  is the diffusion radius, and  $dN_0/dt_i \equiv Q_0 E_p^{-\Gamma}$  is the total escaping rate at time  $t_i$ . Here the diffusion coefficient is assumed to be in the form of  $D(E_p) = 10^{28} \chi(E_p/10\text{GeV})^\delta \text{cm}^2 \text{s}^{-1}$ , where  $\chi$  is the correction factor of slow diffusion around the SNR (Fujita et al. 2009) and  $\delta \approx 0.3-0.7$  (Berezinskii 1990). The number of protons with energy  $E_p$  escaping from the SNR shock front surface at  $t_i$  and arriving at the spherical surface of radius  $R_c$  at  $t_{\text{age}}$  is  $4\pi R_s^2 \int_0^{2\pi} \int_0^\pi f(E_p, R(t_i, \theta, \phi), t_{\text{dif}}) R_c^2 \sin \theta d\theta d\phi$ .

Because of spherical symmetry, the distribution function of protons (escaping from  $R_s(t_i)$ ) for any point (e.g., point C) on the spherical surface of radius  $R_c$  is  $R_s^2 \int_0^{2\pi} \int_0^\pi f(E_p, R(t_i, \theta, \phi), t_{\text{dif}}) \sin \theta d\theta d\phi$ . Therefore, the distribution function for point C accumulating all the historical contributions can be obtained as

$$F_{\text{ac}}(E_p, R_c, t_{\text{age}}) = \int_0^{t_{\text{age}}} \int_0^{2\pi} \int_0^\pi f(E_p, R(t_i, \theta, \phi), t_{\text{dif}}) R_s^2 \sin \theta d\theta d\phi dt_i. \quad (2)$$

For the dynamical evolution of radius of the SNR expanding in the interstellar (intercloud) medium of density  $\rho_0 = 1.4m_{\text{H}}n_0$ , we use the Sedov-Taylor law  $R_s = (2.026 E_{\text{SNR}} t^2 / \rho_0)^{1/5}$  for the adiabatic phase and  $R_s = (147 \epsilon E_{\text{SNR}} R_t^2 t^2 / 4\pi \rho_0)^{1/7}$  for the radiative phase, where  $R_t$  is the transition radius from the Sedov phase to the radiative phase,  $E_{\text{SNR}}$  is the supernova explosion energy, and  $\epsilon$  is a factor equal to 0.24 (Blinnikov et al. 1982; see also Lozinskaya 1992).

The total energy of the escaping protons is  $W_p \equiv \eta E_{\text{SNR}} = t_{\text{age}} \int Q_0 E_p^{-\Gamma} E_p dE_p$ , where  $\eta$  is the fraction of the explosion energy converted into protons.

In addition to the escaping protons, we also consider the contribution of diffuse Galactic protons in the Solar neighborhood with flux density (see, e.g., Dermer 1986):

$$J_{\text{CR}}(E_p) = 2.2 \left(\frac{E_p}{\text{GeV}}\right)^{-2.75} \text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1} \text{sr}^{-1}. \quad (3)$$

In the calculation of the  $\gamma$ -rays from the nearby MC (of mass  $M_c$ ) due to p-p interaction so as to match the observed GeV and TeV fluxes, we use the analytic photon emissivity  $dN_\gamma/dE_\gamma$  developed by Kelner et al. (2006). At high energies,

$$\frac{dN_\gamma}{dE_\gamma} = cn_b \int_{E_\gamma}^\infty \sigma_{\text{inel}}(E_p) J_p(E_p) F_\gamma\left(\frac{E_\gamma}{E_p}, E_p\right) \frac{dE_p}{E_p} \quad (4)$$

where  $n_b$  is the average density of target baryons of the cloud,  $\sigma_{\text{inel}}$  is the cross section of inelastic p-p interactions and function  $F_\gamma(x, E_p)$  is defined by Eq. (58) in Kelner et al. (2006); while at low energies, with the modified  $\delta$ -function approximation as proposed in Aharonian & Atoyan (2000), the emissivity of  $\gamma$ -rays is

$$\frac{dN_\gamma}{dE_\gamma} = 2 \int_{E_{\text{min}}}^\infty \frac{q_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} dE_\pi \quad (5)$$

where  $E_{\text{min}} = E_\gamma + m_\pi^2/4E_\gamma$ , and the production rate of  $\pi^0$  mesons is

$$q_\pi(E_p) = \tilde{n} \frac{cn_{\text{H}}}{K_\pi} \sigma_{\text{inel}}\left(m_p + \frac{E_\pi}{K_\pi}\right) J_p\left(m_p + \frac{E_\pi}{K_\pi}\right) \quad (6)$$

(see Kelner et al. 2006 for the explanations of other parameters).

The contribution of  $\gamma$ -rays from the secondary leptons that are created by p-p interaction is negligible, as compared with the dominant contribution of the protons themselves (Gabici et al. 2007; 2009). Because the timescale for the secondaries to escape from the cloud is shorter than the energy loss time for particle energies between  $\sim 100$  MeV and a few 100 TeV, a large amount of the secondaries produced within clouds of a wide range of parameters escape without being affected by significant losses (Gabici et al. 2009). In

**Table 1.** Parameters of the model considered for different sources.

Variable	$R_c/\text{pc}$	$\delta$	$M_c/10^4 M_\odot$	$n_b/\text{cm}^{-3}$ <sup>a</sup>
source N	12	0.45	4	$1.6 \times 10^3$
source B	22	0.35	0.2	$1.1 \times 10^2$
source A <sub>min</sub>	100	0.6	3.2	$1.8 \times 10^3$
source A	140	0.65	8	$4.4 \times 10^3$
source A <sub>max</sub>	180	0.7	13	$7.2 \times 10^3$
source C <sub>min</sub>	55	0.55	0.64	$1.0 \times 10^3$
source C	100	0.6	2.4	$3.9 \times 10^3$
source C <sub>max</sub>	250	0.7	22	$3.5 \times 10^4$

<sup>a</sup> The adoption of the average angular diameter of each source for deriving the baryon density  $n_b$  is described in the text in §3.

the molecular gas of density as high as  $10^4 \text{ cm}^{-3}$ , the magnetic field could be assumed to be of order  $10^2 \mu\text{G}$  (Crutcher 1999). Extremely high energy ( $\gtrsim$  a few 100 TeV) secondaries radiate all their energy by synchrotron peaked at tens of keV before escaping from the cloud; but the X-rays are not in the scope of this letter.

### 3 APPLICATION TO SNR W28

Now we use the accumulative diffusion model established above to reproduce the GeV–TeV spectra for the four  $\gamma$ -ray sources around SNR W28, showing that the different  $\gamma$ -ray spectra of the four sources mainly result from the different spectra of the runaway protons, as a consequence of the different distances of the sources (molecular clouds) from the SNR shock from which the accelerated protons escape.

The current radius of W28 is approximated as  $R_{\text{SNR}} \sim 12 \text{ pc}$  by using 2kpc as the distance to it. The current blastwave velocity  $v_{\text{SNR}}$  was inferred to be in the  $60\text{--}100 \text{ km s}^{-1}$  range based on the optical observations (see Rho & Borkowski 2002), and hence we adopt  $v_{\text{SNR}} = 80 \text{ km s}^{-1}$ . Also following Rho & Borkowski (2002), we adopt the intercloud medium density  $n_0 \sim 10 \text{ cm}^{-3}$ . For the evolution in the radiative phase, its age is estimated as  $t_{\text{age}} \sim 2R_{\text{SNR}}/(7v_{\text{SNR}}) = 4.2 \times 10^4 (R_{\text{SNR}}/12 \text{ pc})(v_{\text{SNR}}/80 \text{ km s}^{-1})^{-1} \text{ yr}$ . The explosion energy is given by  $E_{\text{SNR}} = 6.6 \times 10^{50} (n_0/10 \text{ cm}^{-3})(v_{\text{SNR}}/80 \text{ km s}^{-1})^{1.2} (R_{\text{SNR}}/12 \text{ pc})^3 \text{ erg}$ . Moreover, we assume a power-law energy spectrum of the escaping protons of index  $\Gamma = 2.2$  (e.g., Giuliani et al. 2010), and adopt  $\chi = 0.1$  (Fujita et al. 2009) and  $\eta = 0.1$  (Blandford & Eichler 1987). Therefore, there are three adjustable parameters:  $R_c$ ,  $\delta$ , and  $M_c$ . These model parameters for the  $\gamma$ -ray sources around SNR W28 are shown in Table 1. All the spectra of the four sources are well reproduced (Figure 2), as described in detail below.

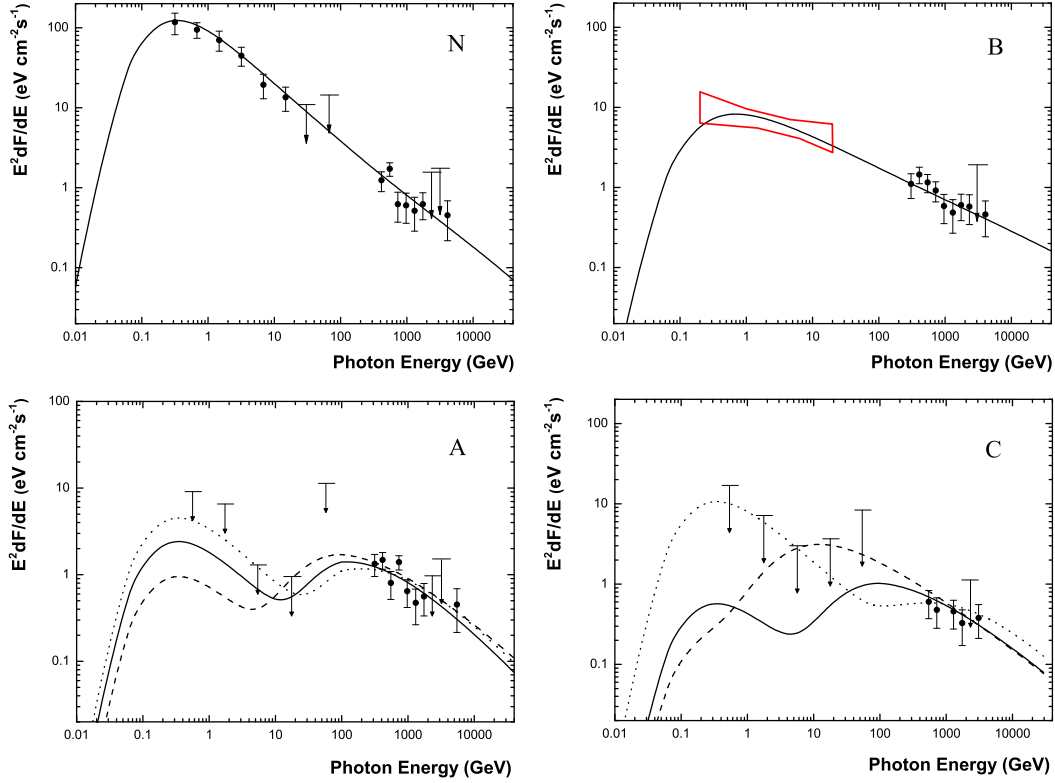
Source N is a well known shock-MC interaction region on the northeastern boundary of SNR W28. We adopt  $R_c \sim R_s(t_{\text{age}}) \sim 12 \text{ pc}$  for this source. The observed GeV spectrum of source N has a spectral break at  $1.0 \pm 0.2 \text{ GeV}$  with photon index 2.1 below the break and 2.7 above the break (Abdo et al. 2010). As seen in the top left panel of Figure 2, this spectral break together with the TeV spectrum can be naturally explained by the accumulative diffusion model without invoking either a breaking power-law

proton spectrum (see Abdo et al. 2010) or any artificial low energy cut-off. The model spectrum peaks at  $\sim 0.35 \text{ GeV}$ . We note that the TeV emission with a slope 2.7 implies the same power-law index for the protons, and this is unlikely to come directly from the shock accelerated protons (because the typical accelerated particle spectral slope for acceleration process is 2–2.3) but can be obtained from a diffusion process.

Source B is located right on the south of SNR W28 with a projected distance of  $\sim 10 \text{ pc}$  from its southern circular boundary (Aharonian et al. 2008), and hence we adopt  $R_c \sim 22 \text{ pc}$ . In source B and also in source N, which are closely near the SNR, the contribution from the diffuse Galactic CRs is negligible compared with that of the diffused protons from the SNR. In our model, with the increase of radius  $R_c$  and hence the increase of the mean diffusion distance, the spectral peak shifts to higher energies. The peak  $\sim 0.62 \text{ GeV}$  for source B (see the top right panel of Figure 2) is higher than the peak in source N, which implies the diffusion effect for different diffusion distances. Source B is also suggested to be associated with HII region W28A2 which may also possibly explain the  $\gamma$ -ray emission, but requires extremely high density of gas (Abdo et al. 2010).

Sources A and C were not found to have significant counterparts in the *Fermi* LAT observation. The LAT upper limits together with the H.E.S.S. data are indicative of a spectral break in the 10–100 GeV range. This break is reproduced in Figure 2 (bottom left panel), in which the concave  $\gamma$ -ray spectra appears as “M” shape with two peaks. The underlying proton spectra consist of two components: the galactic proton background, which is responsible for the left peak, and the protons coming from SNR W28, which are for the right one. With the increase of  $R_c$ , the flux density of CRs accelerated by the SNR is diluted and, compared with the SNR protons, the relative significance of the diffuse Galactic protons rises. There are uncertainties in the GeV fluxes for both sources A and C. The lower limits of  $R_c$  (dotted lines in the bottom left panel of Figure 2) are used for the  $\gamma$ -rays produced by protons escaped from SNR to match the upper limits of the LAT data, and the upper limits of  $R_c$  (dashed line in the bottom left panel of Figure 2) are for the diffuse Galactic protons to match the LAT upper limits. Meanwhile, with  $R_c$  increased, the (right) peak of the emission of the escaping SNR protons now shifts to higher energy than that for source B, thus forming the spectral break at 10–100 GeV. Although there is less confinement in the GeV realm for source C, we can determine the upper and lower limits of  $R_c$  of the source (see the dotted and dashed lines in the bottom right panel of Figure 2), in a similar way used for source A. The fitted values of  $R_c$  for the both sources are much larger than those of sources N and B (see Table 1), which maybe the basic reason why the GeV emission for A and C looks faint.

The estimated mass of northeastern cloud (corresponding to the  $\gamma$ -ray source N) from NANTEN data is  $\sim 5 \times 10^4 M_\odot$  and the total mass of the southern clouds (including the clumps corresponding to sources A, B, and C) is  $\sim 10^5 M_\odot$  (Aharonian et al. 2008). The values of  $M_c$  fitted for the four sources in our model (Table 1) seem to be in agreement with the NANTEN observation. Using the average angular diameters of sources N, A, B, and C,  $18'$ ,  $16'$ ,  $16'$ , and  $12'$ , respectively, as measured from the outermost



**Figure 2.**  $\gamma$ -ray spectral data of the four sources and the model spectra. The observed GeV and TeV data are adapted from Abdo et al. (2010) and Aharonian et al. (2008), respectively. The model parameters are given in Table 1. The dashed and dotted lines represent the model spectra for the upper and lower limits of  $R_c$ , respectively, for both sources A and C (see text in §3).

contours of the TeV emission in Figure 1 in Aharonian et al. (2008), we give the baryon density for each molecular cloud in Table 1 also.

The reproduction of the four  $\gamma$ -ray spectra produces various values of parameter  $\delta$  in the range of 0.35–0.7. The diffusion process of CRs results from particle scattering on random MHD waves and discontinuities. Theoretically, the power-law index of diffusion,  $\delta$ , then depends strongly on the spectral energy density of interstellar turbulence which would originate from fluid instabilities and magnetic field fluctuations. However, the mechanisms of the turbulent phenomena are still in hot debate. In general, three types of isotropic diffusion scalings (Kolmogorov,  $\delta = 1/3$ ; Kraichnan,  $\delta = 1/2$ ; and Bohm,  $\delta = 1$ ) may exist in the ISM (see Strong et al. 2007). The  $\delta$  values obtained in our model vary just between these values and may arise from one or a combination of the three types of diffusion, in view of the fact that the escaping protons diffuse to the four MCs though a nonuniform and anisotropic interstellar environment around SNR W28.

## 4 CONCLUSION

An accumulative diffusion model has been established and well explains the  $\gamma$ -ray spectra of the four sources around SNR W28 recently obtained by H.E.S.S. and *Fermi*. The energetic protons colliding the nearby MCs are considered to be an accumulation of the diffusive protons escaping from the shock front throughout the history of the SNR expansion. For the various distances of the MCs from the SNR centre, the resulted proton spectra can have prominently different shapes. We have thus fitted the  $\gamma$ -ray spectra of the four sources and naturally explained the GeV spectral break of the northeastern source N and the nonsignificant GeV emissions of the southern sources A and C. The distances of sources A and C from the SNR centre are found to be much larger than those of sources N and B. This also implies prospects for inferring the spatial position of the proton-illuminated MCs around SNRs using the GeV and TeV spectra.  $\gamma$ -rays from molecular clouds illuminated by accumulated diffusive protons from SNR W28 strongly support the scenario that hadrons accelerated by SNR shocks contribute to the Galactic CRs.

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